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Developing a Model to Evaluate Maintenance Operations

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To the Graduate Council:

I am submitting herewith a thesis written by Soundararajan Kannan entitled "Developing a Model to Evaluate Maintenance Operations." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Rapinder Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

Ramon Leon, Xueping Li

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Interim Dean of Graduate Studies

Developing a Model to Evaluate Maintenance Operations

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My parents have always encouraged and guided me to achieve higher levels in my life and I am grateful to them. Finally, I thank almighty for being with me through out my life.

ABSTRACT

Maintenance has become a prominent function in today's manufacturing environment. Tremendous efforts have been put into in developing different types of maintenance strategies for enhancing the performance of the equipment but very little has been done in actually streamlining maintenance activities. This refers to systematically evaluating and analyzing the non-value added activities within the maintenance function. One of the primary lean tools that can provide a different dimension in identifying and analyzing non-value added activities is Value Stream Mapping (VSM). However, the traditional VSM cannot be utilized "as is" because the maintenance activities do not completely correspond with VSM terminology. The purpose of this thesis is to develop a simulation based maintenance value stream mapping model to identify and analyze the non-valued activities within the maintenance function.

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Introduction

1.1. Introduction

This introductory chapter begins with the rationale behind the development of this thesis, which is the need for a model to evaluate the maintenance function. It then proceeds to state the problem statement that outlines the objective of this research. Further the chapter provides a brief description regarding the proposed approach undertaken during the course of this research to achieve the objective as defined in the problem statement. The chapter concludes with an overall view of the organization of this thesis in the subsequent chapters.

1.2. Need to Evaluate Maintenance Operations

The ability of the manufacturers to keep up with key business metrics such as cost, quality and on time delivery depends upon the availability and capability of equipment within the manufacturing processes. The emphasis on equipment explicitly demands effective and efficient maintenance because maintenance is viewed as a primary mechanism to ensure the availability and capability of equipment to meet customer expectations. Significant efforts have been made in selecting appropriate maintenance strategies as compared to systematically streamlining the maintenance function. The non-value added activities within a maintenance function can significantly reduce the availability of the machine and also increase the maintenance costs.

With the modern manufacturers trying to strive for Lean in order to reduce inventory, production lead time, direct labor, indirect labor, space requirements, quality costs and material costs [18], the emphasis on equipment availability has become even more critical in order for the manufacturers to successfully implement and sustain Lean. One example is cellular manufacturing, a concept of lean, in which equipments are grouped together according to the process sequence to form a cell. These cells are extremely efficient in achieving single piece flow of product but at the same time extremely susceptible. The susceptibility is due to the fact that cells are highly dependent on equipment availability. When an equipment breaks down in a manufacturing cell, it shuts down the entire production line, until the equipment is brought back to its normal working condition. Hence high amount of non-value added time between machine stoppage and completion of repair, compounds the production loss.

Another dimension for streamlining maintenance activities is the cost associated with downtime. The cost of maintenance downtime as stated by Cooper [16] is typically $500 per hour for a stand-alone machine, $1,500 to $8,500 per hour for a cell or line of machines, and up to $3,500 per minute ($181,500 per hour) for an entire auto factory line. Further, the cost of downtime in lean manufacturing environment is five to thirty times more than other manufacturing environment as it directly and immediately results in lost opportunities [19]. Maintenance cost is directly proportional to the downtime hours and hence increase in the downtime hours due to non-value added maintenance activities can alarmingly increase the maintenance costs.

Thus, there is an immediate need for an approach that explicitly evaluates the maintenance function to eliminate any unnecessary time between machine stoppage and the completion of the repair function. One of the primary lean tools that can provide a different dimension in identifying and analyzing non-value added activities is Value Stream Mapping (VSM). However, the traditional VSM cannot be utilized "as is" because the maintenance activities do not completely correspond with VSM terminology. The purpose of this thesis is to develop a VSM specifically for maintenance, which in essence can be utilized to identify the non-value added activities and the efficiency of the maintenance function.

1.3. Problem Statement

The research work carried out in this thesis focuses on fulfilling the following objectives:

- To develop a VSM specifically for the maintenance in order to evaluate the non-value added time, value added time and the efficiency of the maintenance function.
- To develop a simulation model to perform a dynamic evaluation by incorporating variation in to Maintenance Value Stream Map (MVSM) and to automate the methodology involved in the calculation of MVSM metrics.

1.4. Approach

A general approach that will be utilized for doing this research work is shown in Figure 1.1. The approach is categorized into three distinct phases. The first phase involves developing a framework for MVSM. This will include all the necessary symbols that will be employed for the mapping process. These symbols will then be classified based on the Mean Maintenance Lead Time (MMLT) category. The second phase involves establishing a step by step standard mapping process by which maintenance practitioners in industry could baseline maintenance activities and form a current state map of the maintenance function. The third phase involves developing a simulation model based on the current state map. The purpose of this model is to evaluate the non-value added activities and the efficiency of the maintenance function by incorporating variation associated with factors such as processing time, waiting time etc., into the current state map.

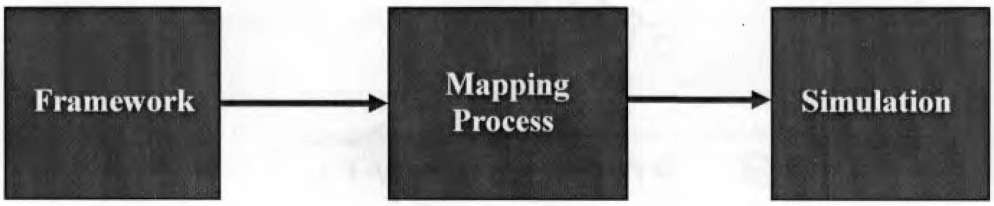


Figure 1.1: Approach

1.4.1. Mean Maintenance Lead Time (MMLT)

The unavailability or downtime consists of three primary categories. The first is the time required from the detection of maintenance activities to the time in which the maintenance tasks are initiated. The second category is the amount of time required to complete the maintenance task and the third category comprises of the time required to yield a good product out of the equipment. The time is categorized into three categories because the root causes that define the time in each category can be quite different. For example the time in the first category may be primarily due to the improper allocation of resources or poor communication between the maintenance operations. The second category may refer to the complexity of maintenance task. The third category focuses on those issues that are related to quality and process capabilities.

Analogous to the concept of lead time in manufacturing, the concept of Mean Maintenance Lead Time (MMLT) is being suggested for maintenance measurement. MMLT is defined as "the time between recognizing the need for maintenance on a particular piece of equipment to the actual performance of such maintenance and the repair of the equipment". [17] MMLT takes the maintenance activities into account from an operational level. Unlike the existing indicators for measuring the maintenance performance, it does not examine the impact of poor or lack of maintenance strategy on the manufacturing front; instead it acts as a powerful tool to measure the maintenance activities themselves. The delineation of MMLT is shown in Figure 1.2

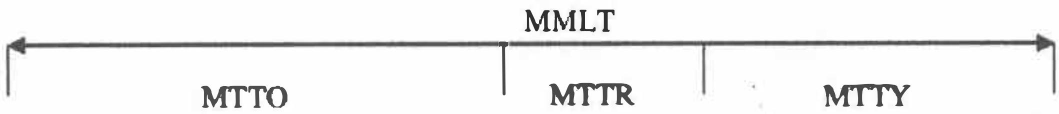


Figure 1.2: Delineation of MMLT

MMLT is given by the following equation.

$$MMLT = MTTO + MTTR + MTTY$$

Where,

MTTO = Mean time to organize (Time required to coordinate tasks to initiate the maintenance repairs)

MTTR = Mean time to repair (Time required to repair and maintain of the equipment)

MTTY = Mean time to yield (Time required to yield a good part after maintenance)

MTTO can be further simplified and represented by the equation below:

$$MTTO = MTTI + MTTC + MTTA + MTTD + MTTL + MTTS$$

Where,

MTTI = Mean time to identify (Identification of failure or maintenance requirements);

MTTC = Mean time to communicate (Communicate maintenance requirements);

MTTA = Mean time to assess (Assessment to identify source of the problem);

MTTD = Mean time to determine (Determine correct parts and tools required);

MTTL = Mean time to locate (Locate and/or order the required parts or equipments);

MTTS = Mean time to schedule (Schedule maintenance for the identified equipments).

1.4.2. Integrating simulation and MVSM

Profozich [20] stated, "You cannot use a static tool to study a dynamic problem. A static tool gives an optimistic performance assessment. The greater the variability in the system, the greater the error in static analysis." The MVSM in essence presents a static picture of a system that breaks the maintenance function into time values (like process time, delay time etc.). In the actual scenario, all these time values are associated with some variation and as stated by Profozich [20], greater the variability associated with these time values, greater the error in static analysis. Hence for the purpose of establishing a dynamic evaluation of the MVSM, an approach that integrates simulation and MVSM is carried out in this research work.

1.5. Organization of thesis

This thesis is comprised of five chapters including this introductory chapter. Chapter 2, "Literature Review", provides a comprehensive review of various VSM tools employed in lean manufacturing. This chapter also throws some light on the need for developing a new VSM tool as the existing tools does not correspond to the maintenance terminology. In addition, this chapter provides details on the current research in the field of lean maintenance. Chapter 3, “Research Methodology” outlines the methodology that is followed in this thesis. It provides a detailed description on developing a new VSM framework and the sequence of steps involved in the mapping process of the maintenance function. Further, it provides description on the use of simulation for a dynamic analysis of the VSM. Chapter 4, “Case Study and Results”, consists of a practical example from industry that illustrates the application of the proposed MVSM to demonstrate its viability. Chapter 5, “Conclusion”, summarizes the major conclusions of this thesis. It also sheds some light on the scope for future research in this area.

Chapter 2

Literature Review

2.1 Introduction

Chapter 2 begins with an introduction to the concept of value stream mapping employed in lean manufacturing and continues to provide a detailed review of the various Value Stream Mapping (VSM) tools. This chapter also provides the recent research in the field of lean maintenance.

2.2 Value Stream Mapping in Lean Manufacturing

The concept of lean manufacturing was popularized by Womack et al [1] as a new production paradigm, which utilizes fewer of all the inputs and creates outputs similar to the mass production system with an increased offering to the end customer by systematically identifying and eliminating the wastes within the manufacturing environment. Monden [2] classified the different activities in a manufacturing in to three types. They are

- Non-Value Adding (NVA). This is a pure waste and involves unnecessary activities, which should be completely eliminated. One common example is wait time.
- Necessary but Non-Value Adding (NNVA). These are activities that are wasteful but necessary for production. An example for this activity would be unpacking the raw material shipments.

- Value-Adding (VA).Those activities that are primarily involved in the conversion of raw material to finished goods and for which the customer is willing to pay for.

Hines & Taylor [3] further classified the wastes or Non-Value Adding (NVA) activities in to seven types which includes

- Overproduction: Producing too much or too soon, resulting in poor flow of information or goods and excess inventory.
- Defects: Frequent errors in paperwork or material/ product quality problems resulting in scrap and/or rework, as well as poor delivery performance.
- Unnecessary inventory: Excessive storage and delay of information or products, resulting in excess inventory and costs, leading to poor customer service.
- Inappropriate processing: Going about work processes using the wrong set of tools, procedures or systems, often when a simpler approach may be more effective.
- Excessive transportation: Excessive movement of people, information or goods, resulting in wasted time and cost.
- Waiting: Long periods of inactivity for people, information or goods, resulting in poor flow and long lead-times.

- Unnecessary motion: Poor workplace organization, resulting in poor ergonomics, e.g., excessive bending or stretching and frequently lost items.

Rother et al [5] demonstrated a tool, known as Value Stream Map (VSM), to systematically identify and analyze the different types of wastes (as listed above) that occur in the manufacturing system. VSM is a tool that helps in visualizing the manufacturing system by the representation of information and material flow. It creates a common language about a production process, by which purposeful decisions can be made to eliminate the non value adding activities.

2.3 Review of VSM tools

2.3.1 Big picture mapping

This mapping tool is used to create an overview of the main features of a production process with a set of pre-defined mapping icons as shown in Figure 2.1. The developed overview will help accomplish the following [3]:

- Visualize the flows.
- Identify where waste occurs.
- Integrate the lean manufacturing principles.
- Show relationships between information and physical flows

There are five different phases involved in big picture mapping [3]. They are

- Define customer requirements.

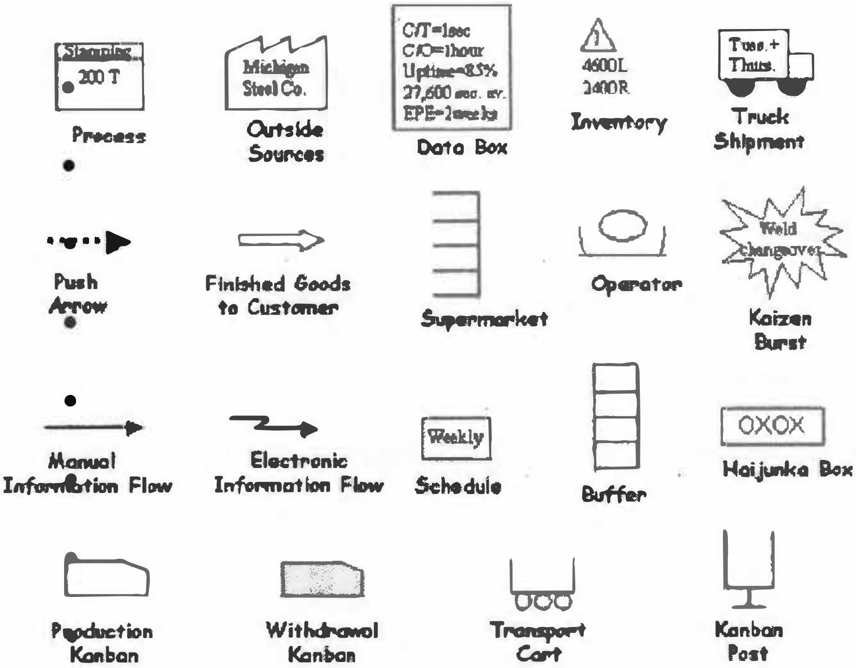


Figure 2.1: Big picture mapping icons [5]

- Map information flows.
- Map physical flows.
- Link physical and information flows
- Complete the map by including a timeline of total lead time vs. the value added time.

During the customer requirements phase, information concerning customer demand, shipment requirements, different parts to be manufactured and customer stock to be held are gathered. In the information flow phase, information on the customer forecast and the way the information is processed within the organization as well as forecast information given to suppliers are gathered. Physical flow phase is concerned with incoming raw materials/components and internal processes. For incoming raw materials information on demand, number of deliveries, delivery quantities, packaging, and lead-times is collected. Internal processes gather information concerning processing time of each process, machine downtime for each process, inventory storage points, inspections, cycle time, set-up time, number of workers, and operation hours per day. Linking the physical and information flows is concerned with the type of scheduling system and work instructions used by the organization. The map is completed by adding a time line at the bottom and recording the production lead-time and the value added time. An example of big picture mapping is shown in Figure 2.2

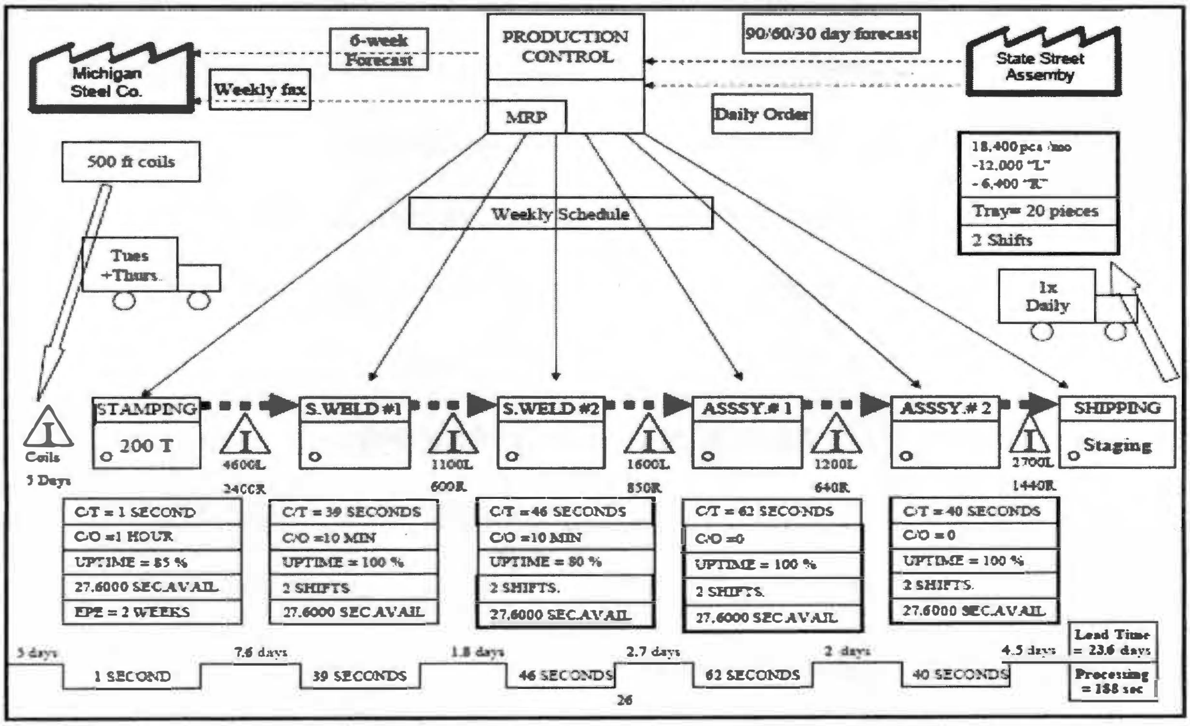


Figure 2.2: Big picture mapping [3, 5]

2.3.2 Supply chain response matrix

The supply chain response matrix has its origins in the time compression and logistics movement [7, 8]. The supply chain response matrix is used to evaluate and portray the inventory levels and critical lead-time constraints for a particular process. It allows the manager to evaluate the need to maintain stock within the context of short lead-time replenishments by identifying large sectors of time and inventory [3].

The horizontal axis represents the cumulative lead time for both the supplier and internal operations. The vertical axis represents the cumulative amount of inventory (in days) at specific points in the supply chain. This shows the typical number of working days of inventory in the system. To develop the chart, the amount of inventory stored and the lead-time required to plan, produce, and move the materials to the next operation are calculated. This information is placed on a simple X-Y chart making sure to use the cumulative amount of time and inventory [3]. Each individual lead-time can then be targeted for improvement, thus focusing on the wastes of waiting, unnecessary inventory, and overproduction [7, 8]. An example of supply chain response matrix is shown in Figure 2.3.

2.3.3 Production variety funnel

This approach originates in the operations management area [10]. It is a visual mapping technique that plots the number of variants at each stage of

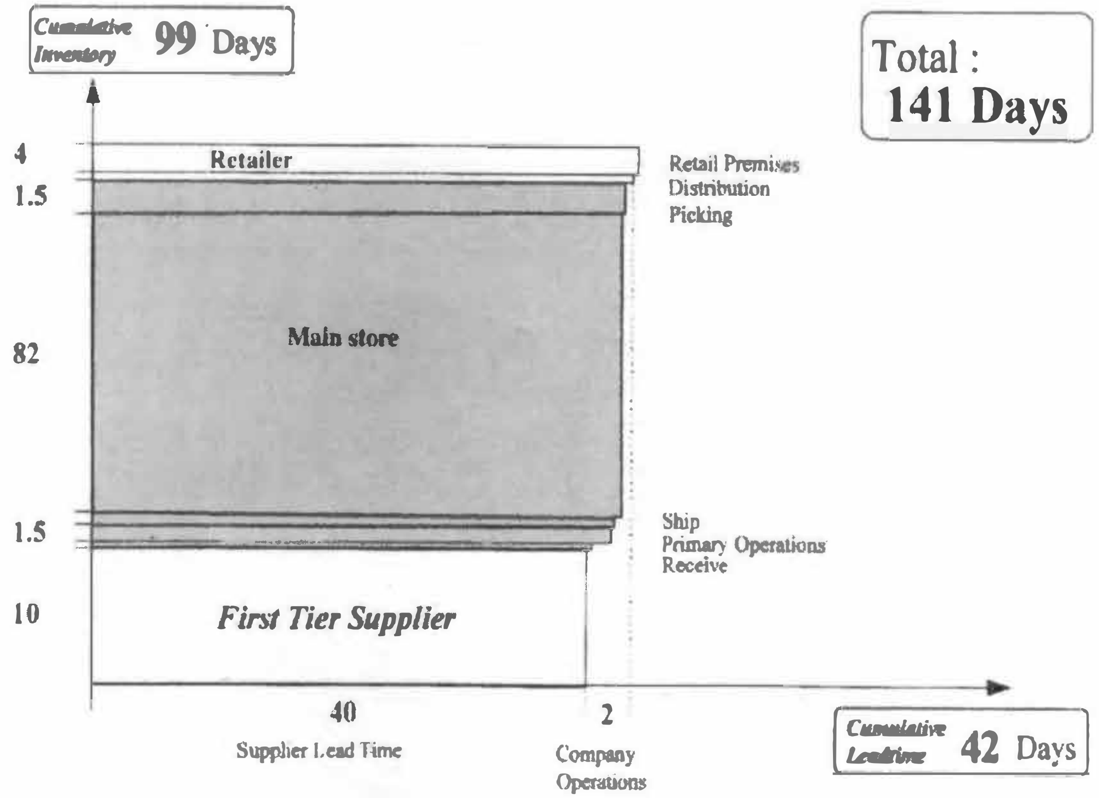


Figure 2.3: Supply chain response matrix [7]

the manufacturing process [12] and is similar to IVAT analysis which views internal operations as consisting of activities that conform to I, V, A, or T shapes as shown in Figure 2.4:

- "I" shapes are used for organizations that consist of unidirectional, unvarying production of multiple items. Chemical plants would be and example of an "I" plant.
- "V" shapes are used for organizations that use limited raw materials processed into a large variety of products. Textiles and metal fabrication industries are examples of "V" plants.

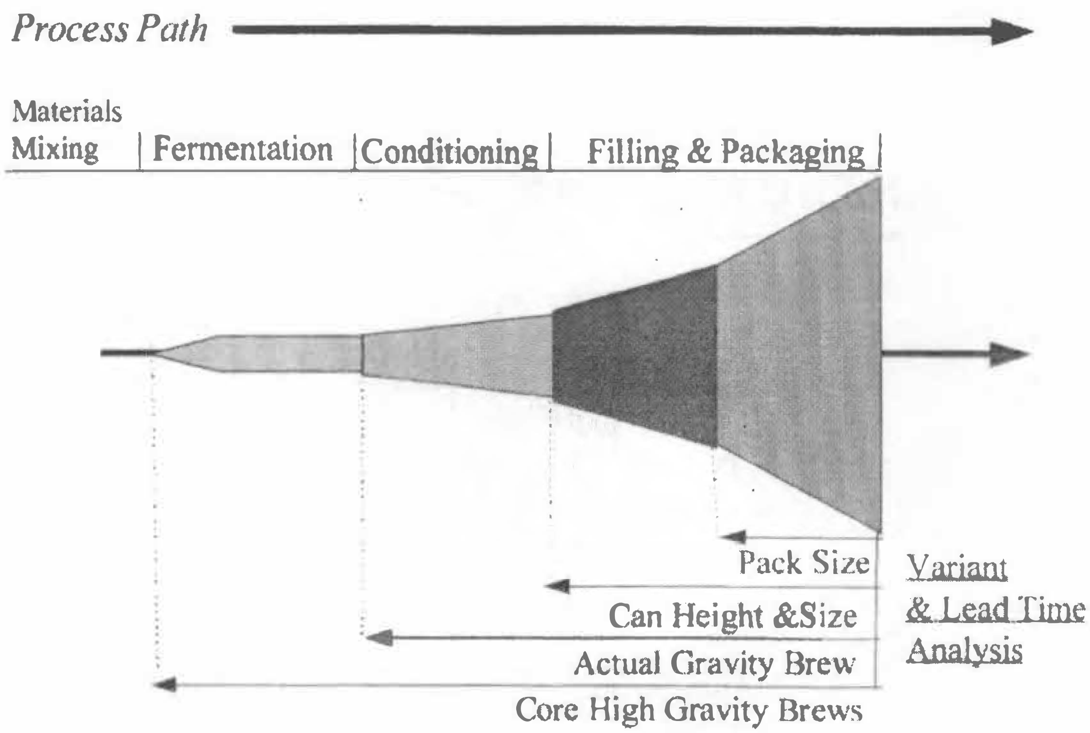


Figure 2.4: Production variety funnel [7]

- "A" shapes are used for organizations that have many raw materials but a limited number of finished products with streams of raw materials using different facilities. The aerospace industry is an example of an "A" shape.
- "T" shapes are used to describe organizations that have a multiple combinations of products using a limited number of components made into semi processed parts used in a range of different versions of final products. The household appliance industry and the electronics industry are example of a "T" shape [7, 8].

The process path is on the horizontal axis and the number of products is on the vertical axis of the production variety funnel. For each product, the process path through the facility is identified. Then the number of products created at each stage of the conversion process is identified, and the final number of outputs produced from each stage is plotted. Such delineation allows the mapper to understand how the supply chain operates and the accompanying complexity that needs to be managed. The production variety funnel can be helpful in identifying where buffer stocks may be held prior to customization, where to target inventory reduction and where to make changes in the processing of products [7, 8]. The production variety funnel focuses on the wastes of inappropriate processing and unnecessary inventory [7, 8].

2.3.4 Quality filter mapping

Quality filter mapping is shown in Figure 2.5. It is a tool developed by Hines and Rich [7] that is used to identify where quality problems exist in the value stream. The map shows where three different types of quality defects occur in the value stream:

- Product defects: Defects found in goods produced that are passed on to the customer.
- Service defects: Defects that are results of an accompanying level of service rather than directly related to the goods themselves. Hines and Rich [7] state that the most important of these service defects is inappropriate delivery in conjunction with incorrect documentation.
- Internal scrap: Defects that are caught prior to delivery to the customer.

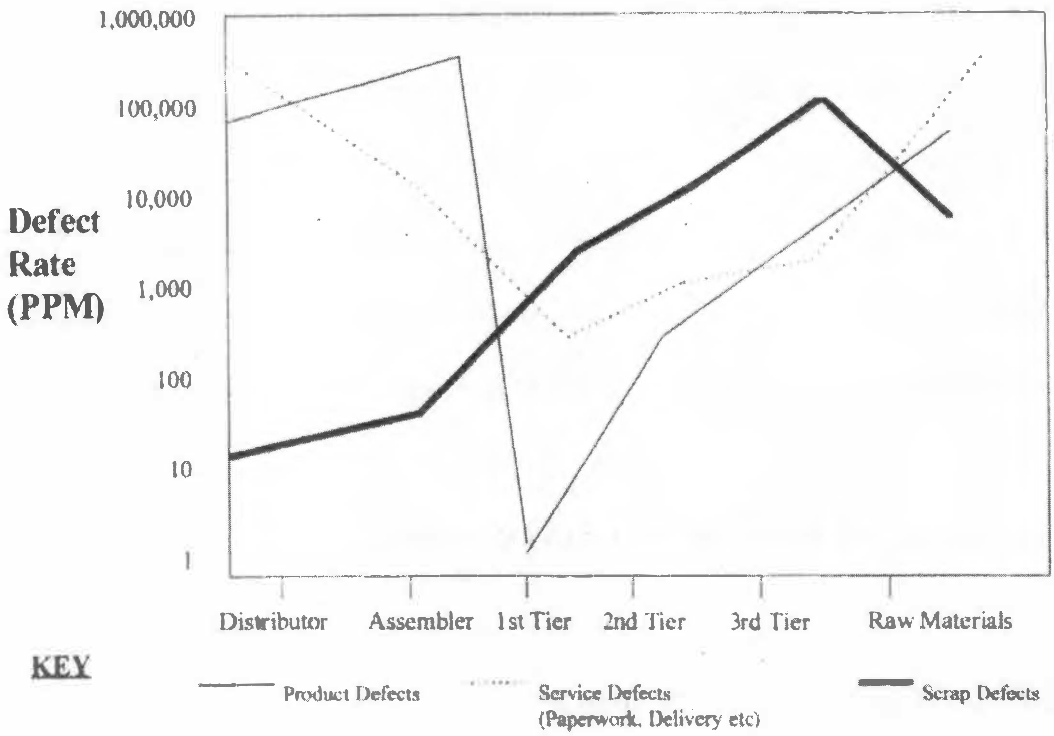


Figure 2.5: Quality filter mapping [7]

Quality filter mapping is designed to establish both internal and external quality levels as well as levels of customer service. Each of the defects is mapped along the supply chain. This can include the distributor; the assembler; first, second, and third tier suppliers; and defects in raw materials. This approach clearly identifies where defects are occurring and thus identifies where there is wasted effort. Quality filter mapping is used primarily to identify the waste of defects. The tool can be used internally by using individual departments or work areas instead of different companies (e.g., suppliers) [3].

2.3.5 Demand amplification mapping

Demand amplification mapping (as shown in Figure 2.6) has its roots in the systems dynamics work of Forrester [11] and Burbidge [12]. It is a graph of quantity against time. It shows the batch sizes of a product at different stages of the production process [3]. It can be used within an organization or along the supply chain. The "bullwhip" or "Forrester effect," where demand changes amplify the further one gets away from the original demand source is an important result of this tool [3]. This tool can be used to:

- Visualize the extent of the amplification as orders move upstream,
- Gain insight into batch scheduling policies and batch sizing by looking at both quantity and timing, and
- Analyze inventory decisions [3].

There are six steps in the development of the demand amplification map [7, 8]:

- Identify the stages to collect data from.
- Identify products to be studied.
- Decide on the time horizon.
- Decide on the analysis period.
- Collect batch size and inventory data.
- Plot.

The demand amplification map is a powerful tool for evaluating inventory and scheduling policies. When using the demand amplification map, mappers must

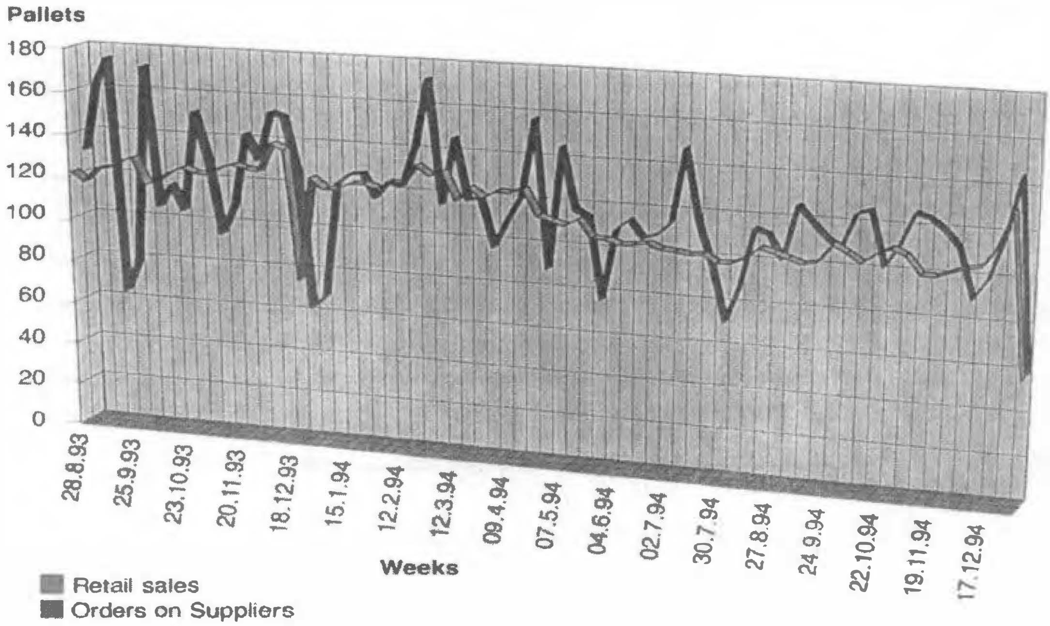


Figure 2.6: Demand amplification mapping [13]

distinguish between the amplification due to changeovers and the amplification due to inventory policies.

There should be low variation in batch sizes and the batches should arrive at regular time intervals [7, 8]. The analysis can provide information that would be helpful in redesigning the value stream and managing fluctuations in demand. Demand amplification mapping focuses on the wastes of unnecessary inventory, overproduction, and waiting [7, 8].

2.3.6 Decision point analysis

The decision point is the point in the value stream where demand-pull gives way to forecast-push [7, 8]. Understanding where this point lies is beneficial for two reasons:

- With respect to the present, this knowledge allows for the assessment of processes that operate both upstream and downstream from this point. This is to ensure alignment with the relevant push or pull philosophy.
- With respect to the long-term, this allows for the development of "what if" scenarios to view the operation of the value stream if the decision point is moved. This may allow for a better-designed value stream.

Decision point analysis focuses on the wastes of overproduction, waiting, and unnecessary inventory [7, 8]. An example of decision point analysis is shown in Figure 2.7.

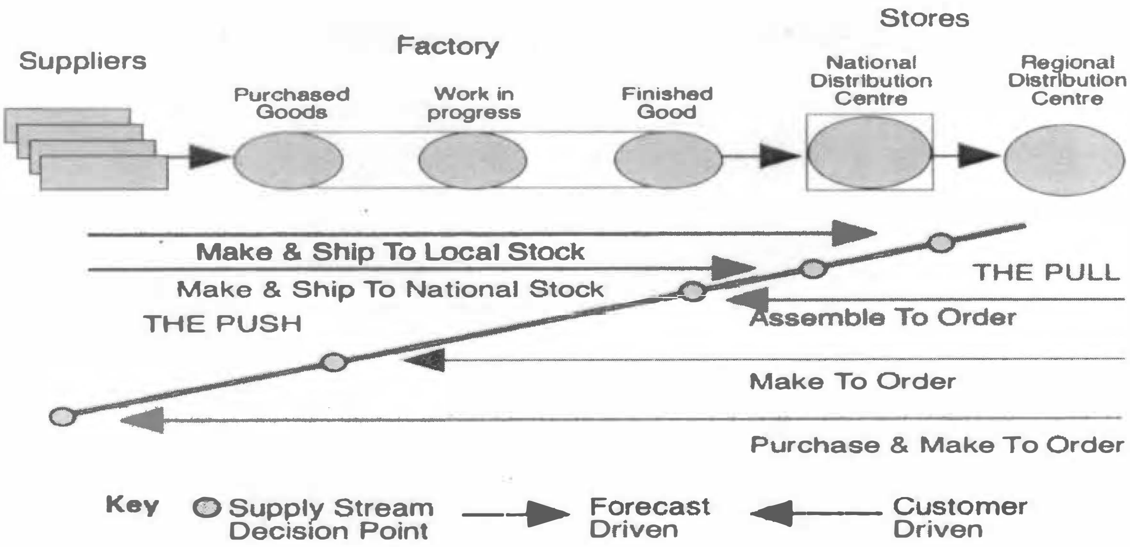


Figure 2.7: Decision point analysis [14]

2.3.7 Physical structure mapping

Physical structure mapping (shown in Figure 2.8) is the second tool that was developed by Hines and Rich [7]. This mapping tool is used to obtain an overview or industry level view of the value stream. This overview is helpful in determining what the industry looks like, how it operates, and in focusing attention to areas that are not receiving sufficient attention. This tool has two parts

- Volume structure and
- Cost structure

Volume structure shows the structure of the industry by the tiers that exist in both the supplier and distribution areas with the assembler located in the middle. Cost structure shows the industry in a similar manner, except that it links the organizations according to the value-added processes. The physical structure map addresses the wastes of transportation and unnecessary inventory [7].

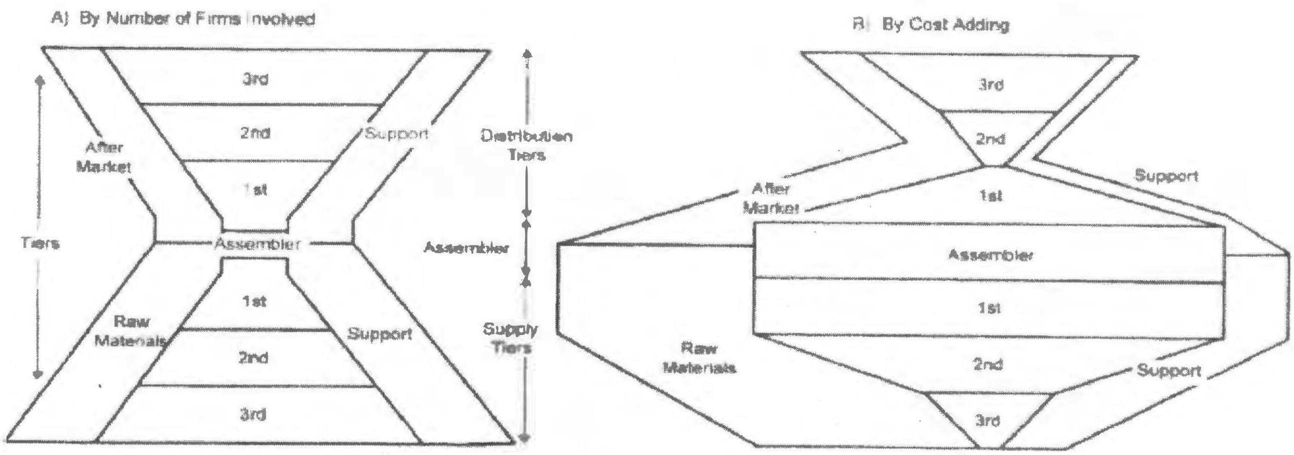


Figure 2.8: Physical structure mapping [7]

2.4 Lean Maintenance

There has been emerging research in the area of applying lean manufacturing principles to the maintenance function in order to eliminate the wastes within maintenance. Bruce Hawkins [15] defined lean maintenance as “the application of Lean philosophy, tools and techniques to the maintenance function”. Analogous to the wastes in lean manufacturing, Bruce [15] classified the wastes within the maintenance function into seven types as

- Overproduction — Excessive use of preventive maintenance, the application of wrong maintenance technologies to the equipment that is under consideration, and repeating the same job again and again since it was not done correctly for the first time.
- Waiting —Maintenance operator waiting for the work order to be released, waiting for resources, waiting for instruction and tools.
- Transportation — Maintenance operator traveling long distances for parts and technical information.
- Processing — Inefficiently designed work order systems that require multiple entries of the same data, excessive and time consuming reporting system that requires redundant approvals and ineffective job plans that create backtracking or unnecessary steps.
- Inventory — Excessive inventory of maintenance tools and spare parts.

- Motion — Unnecessary movement of the maintenance staff due to poor shop or storeroom layouts; poor storage techniques for O&M manuals, drawings and loop sheets; and not kitting materials for planned work.
- Defects —Defects due to poor workmanship resulting from inadequate training, ineffective procedures and not having proper tools to do the job, improper storage and handling of spare parts, inadequate methods for equipment installation.

Bruce [15] also proposed the adaptation of lean manufacturing principles such as 5S, Kaizen, Jidoka and Just in Time (JIT) to the maintenance function in order to eliminate the above mentioned different types of wastes.

2.5 Conclusion for Literature Review

The various VSM tools that are employed in lean manufacturing were reviewed. However none of these tools can be applied as it is simply because they do not directly correspond to the maintenance terminology. Further, the literature review on lean maintenance reveals that the lean manufacturing philosophies such as 5S, Kaizen, Jidoka and JIT are being adapted to the maintenance in order to eliminate non-value added activities. However applying all these lean tools to each and every area within maintenance will involve tremendous amount of time and money. Hence there is a definite need of a VSM tool for the maintenance, as it evaluates the maintenance function and indicates critical areas within maintenance, where non-value added activities need to be eliminated.

Chapter 3

Research Methodology

3.1 Introduction

Chapter 3 charts out the systematic procedure involved in the development of MVSM. As illustrated in chapter1, the methodology involves three phases. Phase 1 involves developing a new framework for MVSM, which will have all the necessary symbols needed for the mapping process. Phase 2 illustrates the step by step mapping process and Phase 3 describes the use of simulation modeling, which provides user friendliness to the model as well as integrates variation in to the MVSM. All these three phases are covered in detail in this chapter.

3.2 MVSM Framework

In this first phase, a general framework is introduced for developing the MVSM as shown in Figure 3.1. Within this framework there are seven categories that are utilized to represent the actual maintenance function. Specifically, these seven categories are utilized to represent MTTO, MTTR, and MTTY. Appropriate MVSM symbols are provided for each of this category. These are a combination of newly developed symbols as well as symbols adopted from the traditional VSM.

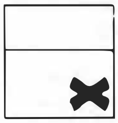
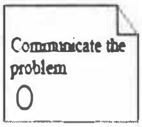
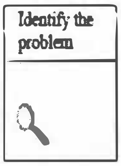
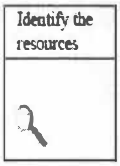
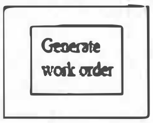
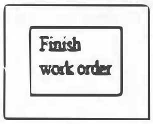
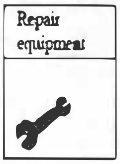
Framework Category	Sub-Category	Symbol	Symbol Name	Definition	MMLT Category
Equipment Breakdown			Equipment Breakdown	The equipment breakdown symbol is used to represent the equipment that has shutdown.	MTTO, MTTR, MTTY
Process	Communication		Communicate the problem	This process involves the communication of the problem by the equipment operator to the maintenance personnel as soon as the equipment shuts down	MTTO
	Identification		Identify the problem	This process involves the identification of the cause of the problem for equipment shutdown	MTTO
			Identify the resources	This process involves the identification of appropriate resources such as tools, spare parts, people etc required for performing the repair work.	MTTO
	Locate		Locate the resources	This process involves locating/ordering the appropriate resources needed for the repair work.	MTTO
	Work order		Generate work order	This process involves generating a maintenance work order through the CMMS system	MTTO
			Finish work order	This process involves completing the maintenance work order through the CMMS system	MTTO
	Repair		Repair equipment	This process involves the operation of actually repairing the equipment	MTTR

Figure 3.1: MVSM Framework

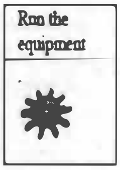
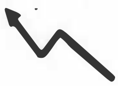
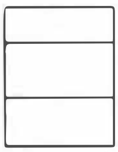
Framework Category	Sub-Category	Symbol	Symbol Name	Definition	MMLT Category
	Yield		Run the equipment	This process involves the operation of an equipment after repair until a good part is produced	MTTY
Physical flow	Push Arrow [5]		Push Arrow	The push arrow represents the physical flow sequence of processes. Two subsequent maintenance processes are connected by this arrow.	MTTO, MMTR, MMTY
	Down Arrow		Down Arrow	The down arrow represents the physical flow between the shut down equipment and the first activity in value stream.	MTTO
Information flow	Manual [5]		Straight Arrow	The straight arrow represents the manual flow of information from memos, reports, or conversation. Frequency and other notes are provided along the line.	MTTO, MMTR, MMTY
	Electronic [5]		Wiggle Arrow	The wiggle arrow represents the electronic flow of information from the internet, intranets, local area network (LAN), wide area network (WAN). Frequency and other notes are provided along the line.	MTTO, MMTR, MMTY
Data box [5]			Data box	The data box is used to record the information of each maintenance process. Typical information placed in this box will be the Process time of each maintenance process	MTTO, MMTR, MMTY

Figure 3.1: Continued

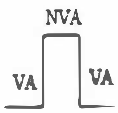
Framework Category	Sub-Category	Symbol	Symbol Name	Definition	MMLT Category
Delay	Unavailability of equipment operator		Delay 1	The delay 1 symbol is used to represent the delay in the initiation of maintenance process due to the unavailability of equipment operator to inform the maintenance personnel about the equipment shut down.	MTTO
	Unavailability of tools & parts		Delay 2	The delay 2 symbol is used to represent the delay due to unavailability of appropriate tools and parts required to perform the maintenance tasks.	MTTO
	Unavailability of appropriate maintenance personnel		Delay 3	The delay 3 symbol is used to represent the delay in the maintenance process due to unavailability of appropriate maintenance personnel.	MTTO, MTTY
Time line [5]			Time line	The time line symbol is used to record information about value added (VA) and non value added (NVA) times Non value added times are recorded on the top of the timeline and value added activities are recorded on the bottom of the timeline.	MTTO, MTTR, MTTY

Figure 3.1: Continued

The following are definitions of each of the seven categories of MVSM Framework.

1. Equipment breakdown – This activity represents the actual event of an equipment to stop production due to maintenance requirements.
2. Processes – These are actual activities that occur from the time an equipment is stopped to the time it is producing good products. In a typical maintenance function, there are eight different processes. They are Communicate the problem, Identify the Problem, Identify the resources, Locate the resources, Generate work orders, Repair equipment, Run the equipment and Finish work order. These activities represent a combination of both value added and non-value added activities.
3. Physical flow -The physical flow sequence of processes is critical to baseline the overall maintenance process. In some case the sequence of processes may illustrate opportunities for improvement.
4. Information flow – The physical flow of processes is dependent upon the flow information to enable the physical flow. It is sometimes the information that is the constraint in the system.
5. Data Boxes – Associated with each process there is a data box that provides information regarding each process. This information is critical in determining the opportunities for improvement.
6. Delay – There is a possibility of delay between any two processes. This delay is viewed as non value added that increases the MMLT and therefore the

responsiveness to the customer. In a typical maintenance function, there are three different types of delay. They are Delay due to unavailability of equipment operator, Delay due to unavailability of tools and parts and Delay due to unavailability of appropriate maintenance personnel.

7. Timeline – The timeline presents two categories of time. The first category is the value-added time and it is typically associated with the processes. The second category is the non-value added time and it is associated with both the processes and delays in the system.

3.3 Mapping Process

This phase describes the mapping process involved in developing the MVSM. The process is presented in the seven steps provided below:

Step 1 involves the following tasks associated with the equipment that has been shut down as presented in Figure 3.2.

- Draw the equipment breakdown symbol for the equipment that has shut down.
- Place this symbol at the top left hand corner of the MVSM page
- Write the equipment name at the top rectangular box.

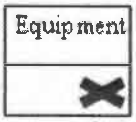


Figure 3.2: Step 1 of MVSM

Step 2 involves identifying the boundary of the process. Specifically this involves identifying the first process after a machine is shut down and the last process when a first good part is produced.

- The first process is associated with symbol “communicate the problem”.
- Place this symbol to the left hand side of the page under the equipment breakdown symbol.
- Place the finish work order symbol to extreme right hand side of the page such that it is aligned with communicate the problem symbol as shown in Figure 3.3

Step 3 involves identifying the intermediate processes between the first process “communicate the problem” and the last process “Finish work order”.

Figure 3.3: Step 2 of MVSM

- The first intermediate process is associated with symbol "Identify the problem". Place this symbol to the right side of communicate the problem symbol.
- The next process is associated with symbol "Identify the resources". Place this symbol to the right side of Identify the problem symbol.
- The next process is associated with symbol "Locate the resources". Place this symbol to the right side of Identify the resources symbol.
- The next process is associated with symbol "Generate work order". Place this symbol to the right side of Locate the resources symbol.
- The next process is associated with symbol "Repair equipment". Place this symbol to the right side of Generate work order symbol.
- The next process is associated with symbol "Run the equipment". Place this symbol to the right side of Repair equipment symbol and make sure all the symbols are aligned as shown in Figure 3.4.

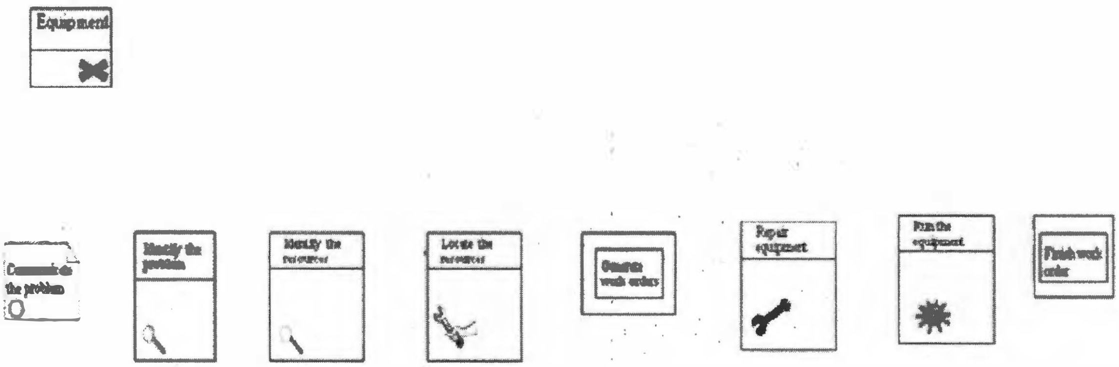


Figure 3.4: Step 3 of MVSM

Step 4 involves recording the information associated with each maintenance process as shown in Figure 3.5

- Place the data box symbol underneath each process.
- Calculate the process time for each process
- Enter the value of the process time in the data box. Arbitrary process time values are assigned for the purpose of illustration.

It should be noted that the finish work order process does not contribute to MMLT and hence its process time is not included.

Step 5 involves recording the delay time between maintenance processes.

- Place the delay symbol between all the processes.

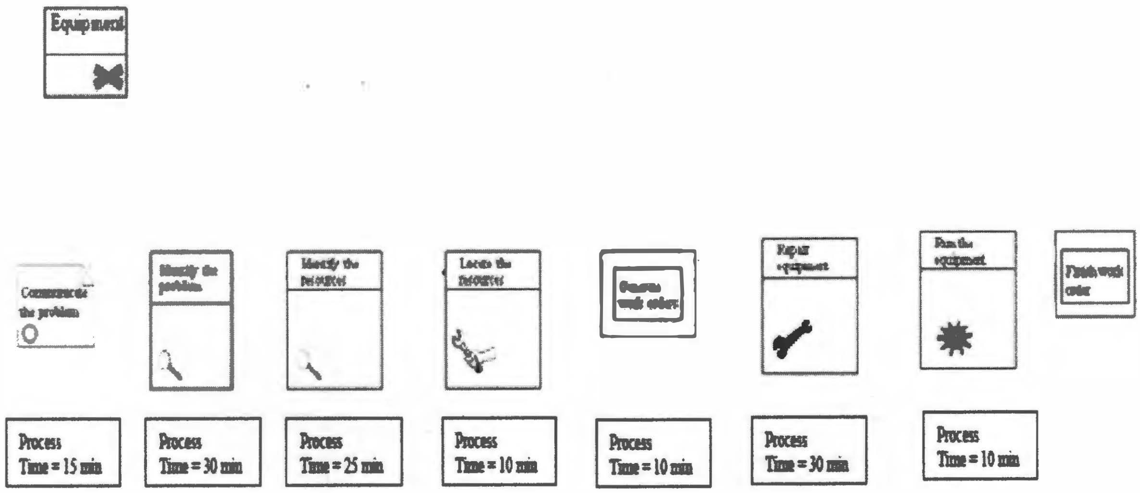


Figure 3.5: Step 4 of MVSM

- Typically in a maintenance function, there are three different types of delays. They are namely, Delay due to unavailability of equipment operator (1), Delay due to unavailability of tools & parts (2) and Delay due to unavailability of appropriate maintenance personnel (3).
- Write the appropriate numbers inside the delay symbol to indicate the type of delay. If there are two or more types of delays associated with a process, write all the numbers corresponding to the delay type separated by comma as shown in Figure 3.6
- Calculate the delay time.
- Write the delay time below the delay symbol. Arbitrary delay time values are assigned for the purpose of illustration

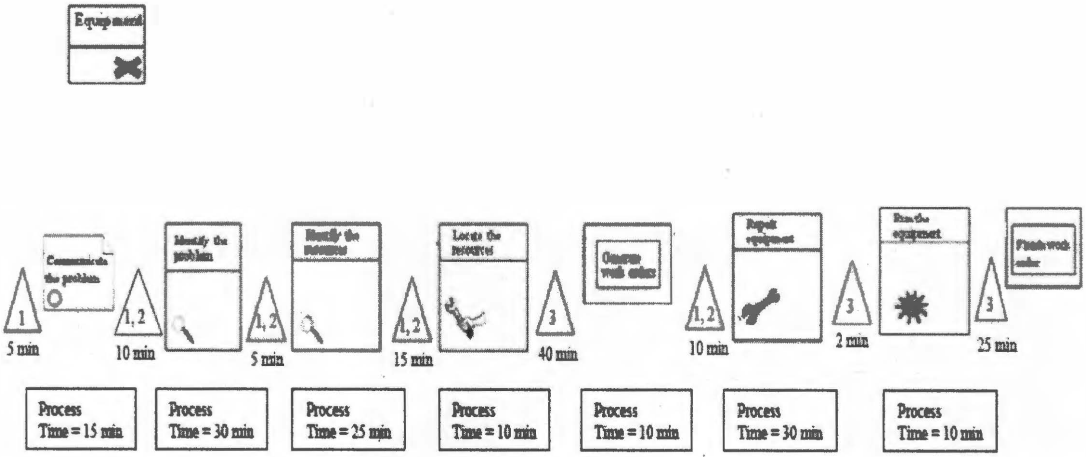


Figure 3.6: Step 5 of MVSM

Step 6 involves creating the physical flow and information flow for maintenance processes.

- Connect the break down equipment with the first activity in the value stream using the down arrow symbol.
- Connect all the processes with physical flow (dashed lines) and information flow (continuous line) arrows as shown in Figure 3.7

Step 7 involves the following tasks associated with the calculation of MMLT, MTTO, MTTR and MTTY

- Draw the time line at the bottom of the page as shown in Figure 3.8
- Write down all the non-value added times at the top of the time line and all the value added times at the bottom of the time line.

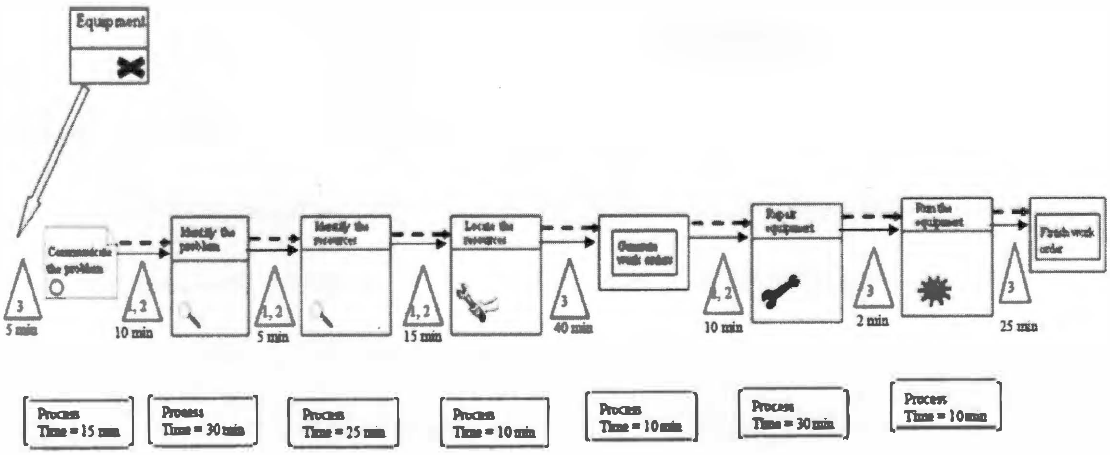


Figure 3.7: Step 6 of MVSM

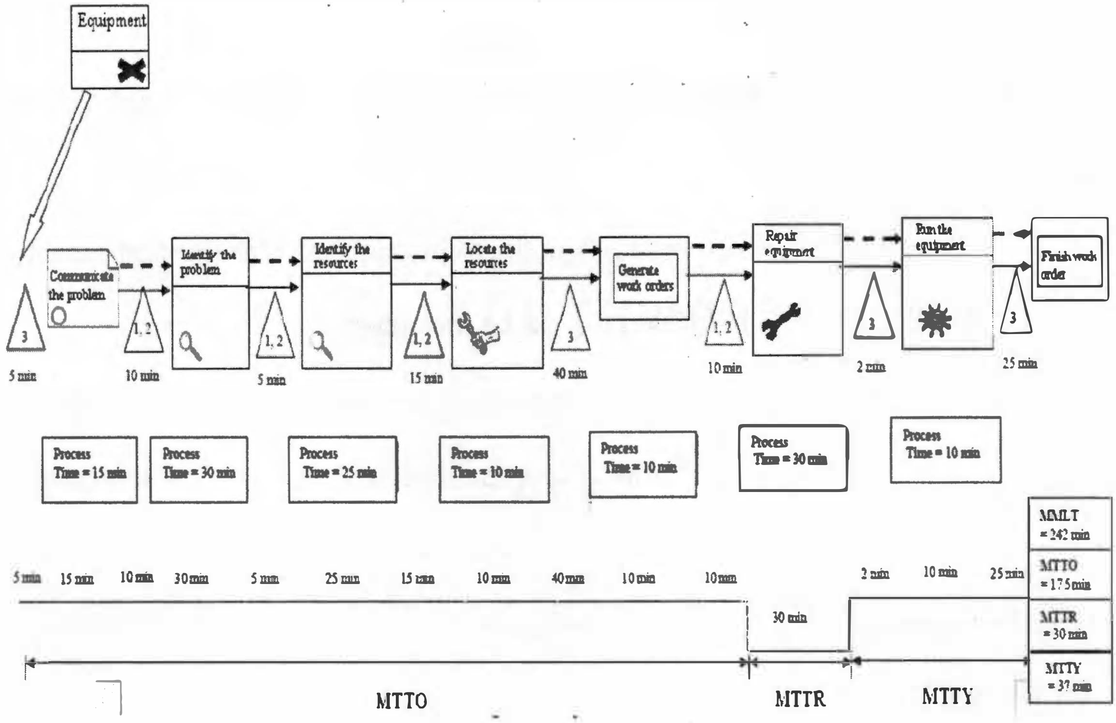


Figure 3.8: Step 7 of MVSM

- Calculate MMLT, MTTO, MTTR and MTTY.
- Evaluate the total non-value added time by summing up MTTO and MTTY

3.4 Simulation of MVSM

This phase involves the use of computer software to incorporate variation into the MVSM and perform a dynamic evaluation of the maintenance function. This will also provide user friendliness to the model, wherein the user can input different time values for all the delays and processes in the MVSM. The simulation will then automatically evaluate non-value added time, value added time and efficiency of the maintenance function and display the results.

A simulation model for MVSM was developed using ARENA 8.0. The model receives input from the user as shown in Figure 3.9.

The simulation inputs; number work orders per year and time between each work order determines the number and the frequency of simulation runs required to evaluate the maintenance function. The other simulation inputs are the MVSM parameters. Values for all the simulation inputs can either be an average value or any type of distribution. Table 3.1 lists the various types of distribution and the format in which it should be given as input to the model.

After getting all the inputs from the user, the simulation automatically calculates MTTO, MTTR, MTTY, MMLT, Non-value added time, Value added time and Maintenance Efficiency. Non-value added time is calculated by summing up MTTO and MTTY. Value added time is MTTR. Maintenance Efficiency is calculated as a percentage of MTTR/MMLT. After performing all the calculations, the simulation displays the results as shown in Figure 3.10.

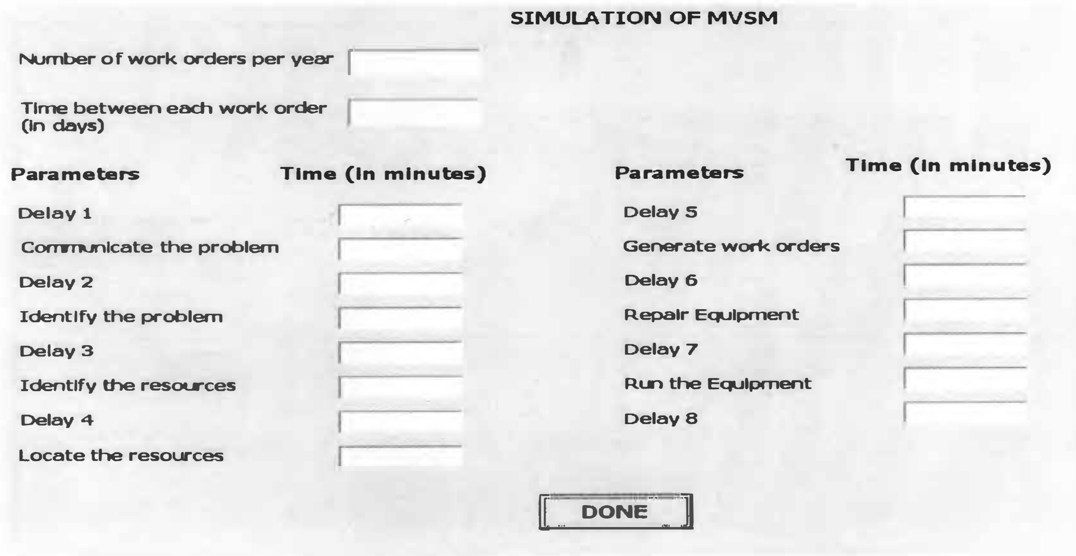


Figure 3.9: Simulation Input screen

Table 3.1: List of Distribution

Type of Distribution	Input Format
Exponential	EXPO(Mean)
Normal	NORM(Mean, StdDev)
Triangular	TRIA(Min, Mode, Max)
Uniform	UNIF(Min, Max)
k-Erlang	ERLA(Expomean, k)
Beta	BETA(Beta, Alpha)
Gamma	GAMM(Beta, Alpha)
Johnson	JOHN(Gamma, Delta, Lambda, Xi)
Lognormal	LOGN(LogMean, LogStdDev)
Poisson	POIS(Mean)
Weibull	WEIB(Beta, Alpha)

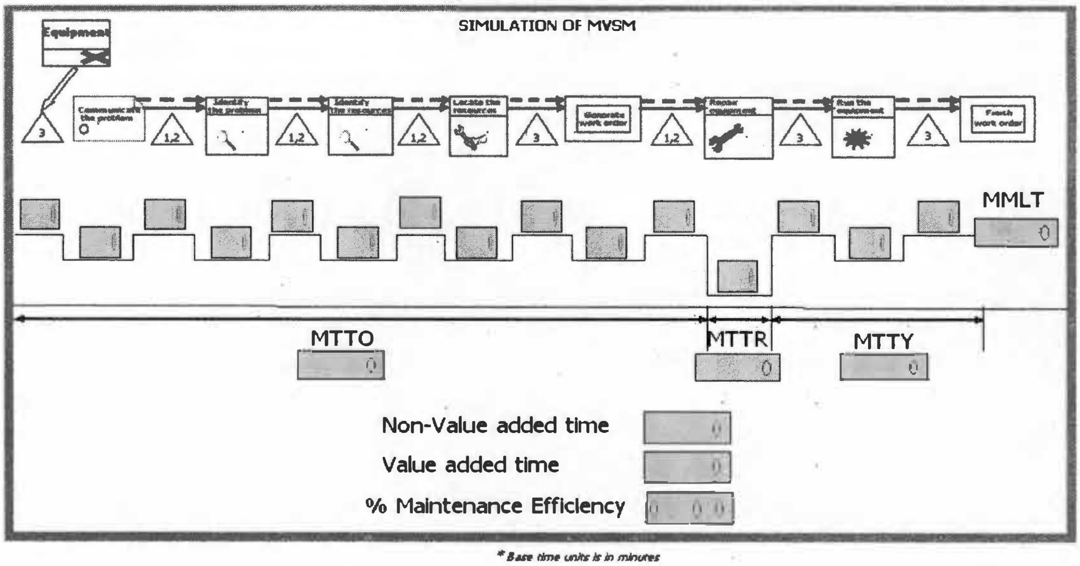


Figure 3.10: Simulation Output Screen

Chapter 4

Case Study and Results

4.1 Introduction

Chapter 4 talks about an industry case study that illustrates the application of the MVSM based on the approach suggested in the previous chapter. Further, the chapter also provides the results for the case study.

4.2 Case Study

Tungsten powder production process as shown in Figure 4.1 will be the basis for the case study. The raw material used for the powder production is tungsten oxide powder. This powder is fed in to the furnace, which converts tungsten oxide into tungsten. The tungsten powder obtained from the furnace is sent to lab (Inspection 1) for determining the grain size of the powder. Various different grain sizes of tungsten powder are blended in the blender to get the appropriate mix of grain size. The tungsten powder from the blender is then sent to the lab (Inspection 2) for a final inspection of the grain size. The inspected tungsten powder is stored in drums for shipping.

The bottleneck process within the production is the furnace operation. Since the downtime of the furnace will impact the production the most, it was decided to develop a MVSM for the furnace. This MVSM will help the practioners to identify the total non-value added time and the efficiency associated with the

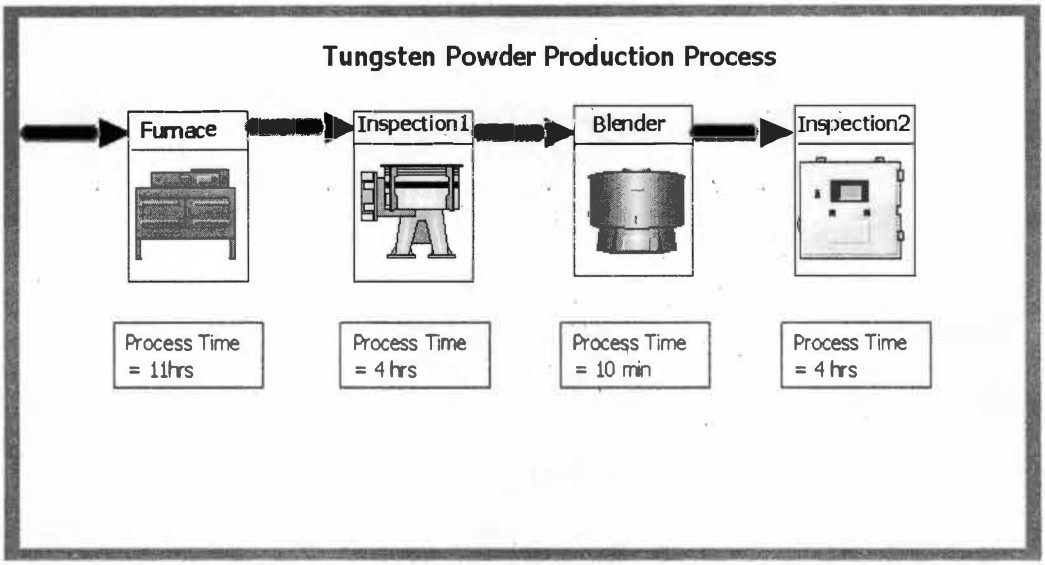


Figure 4.1: Tungsten Powder Production Process

maintenance of the furnace as soon as it breaks down and will also enable them to take appropriate actions in order to reduce the non-value added time.

4.3 Mapping Process

The mapping process involved in developing MVSM for furnace is presented in the seven steps shown below.

Step 1: In this case study, the equipment that has shut down is furnace. Hence the name “Furnace” is written on the equipment breakdown symbol and it is placed on the top left hand corner of the MVSM page as shown in Figure 4.2.

Step 2: The first and last processes were identified as “Communicate the problem” and “Finish work order”. Hence the two process symbols were placed at the extreme end of the MVSM page as shown in Figure 4.3.

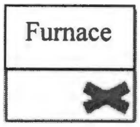


Figure 4.2: Step 1 of MVSM (Case Study)

Figure 4.3: Step 2 of MVSM (Case Study)

Step 3: The intermediate processes were identified as “Identify the problem”, “Identify the resources”, “Locate the resources”, “Generate work order “, “Repair equipment” and “Run the equipment”. Symbols corresponding to the intermediate processes were placed right next to each other as shown in Figure 4.4

Step 4: Data box symbol was placed underneath each process and the appropriate process time value obtained from the industry was also recorded as shown in Figure 4.5.

It should be noted that the finish work order process does not contribute to MMLT and hence its process time is not included.

Step 5: Delay symbol was placed between each process as shown in Figure 4.6. Type of delay and delay time were recorded based on the case study data

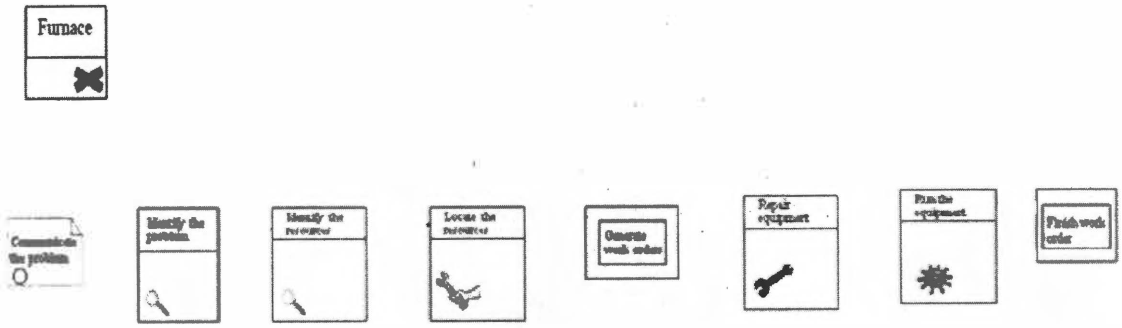


Figure 4.4: Step 3 of MVSM (Case Study)

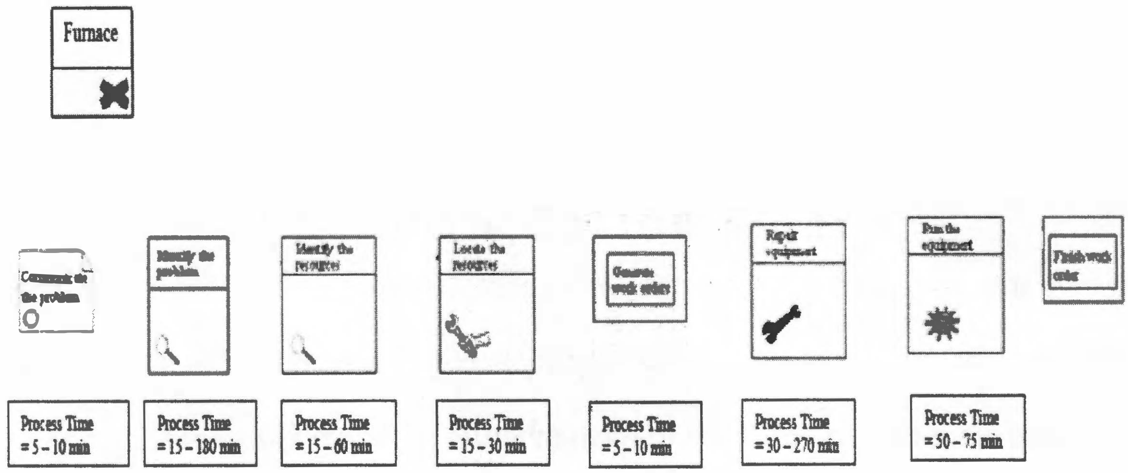


Figure 4.5: Step 4 of MVSM (Case Study)

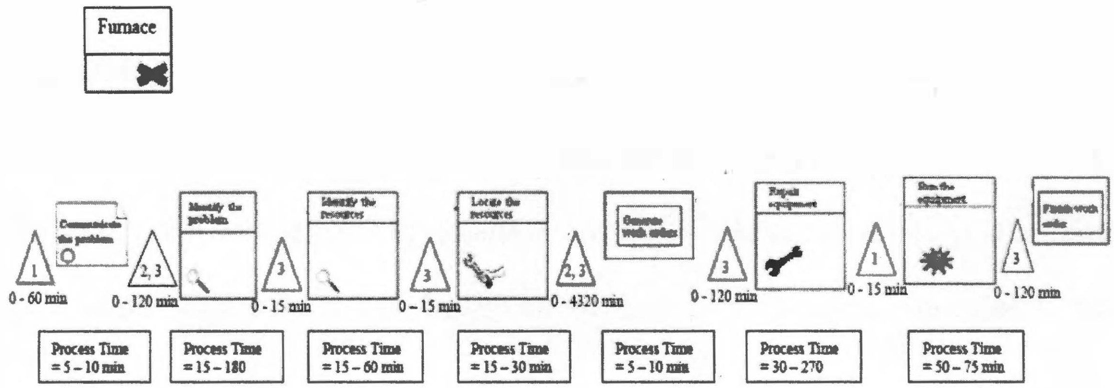


Figure 4.6: Step 5 of MVSM (Case Study)

Step 6: The break down equipment "Furnace" was connected to the first activity in the value stream using the down arrow symbol. All the processes were connected with physical flow (dashed lines) and information flow (continuous line) arrows as shown in Figure 4.7.

Step 7: The time line was drawn at the bottom of the MVSM page as shown in Figure 4.8. All the non-value added times were recorded at the top of the time line and all the value added times were recorded at the bottom of the time line. Simulation model shown in the next section was utilized to calculate the MTTO, MTTR, MTTY, MMLT, Total Non-Value added time and Efficiency of the maintenance function.

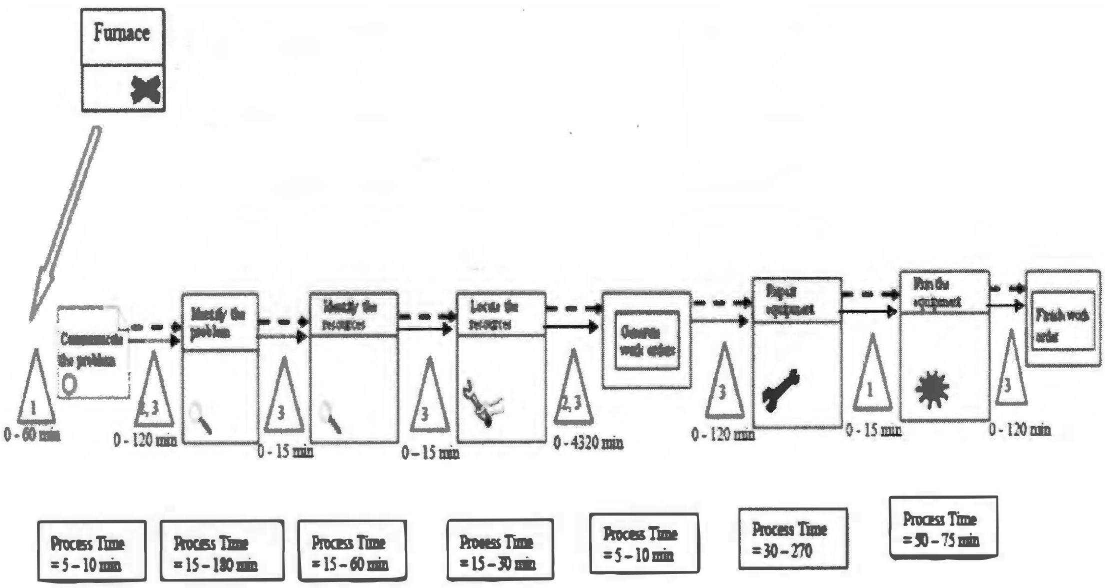


Figure 4.7: Step 6 of MVSM (Case Study)

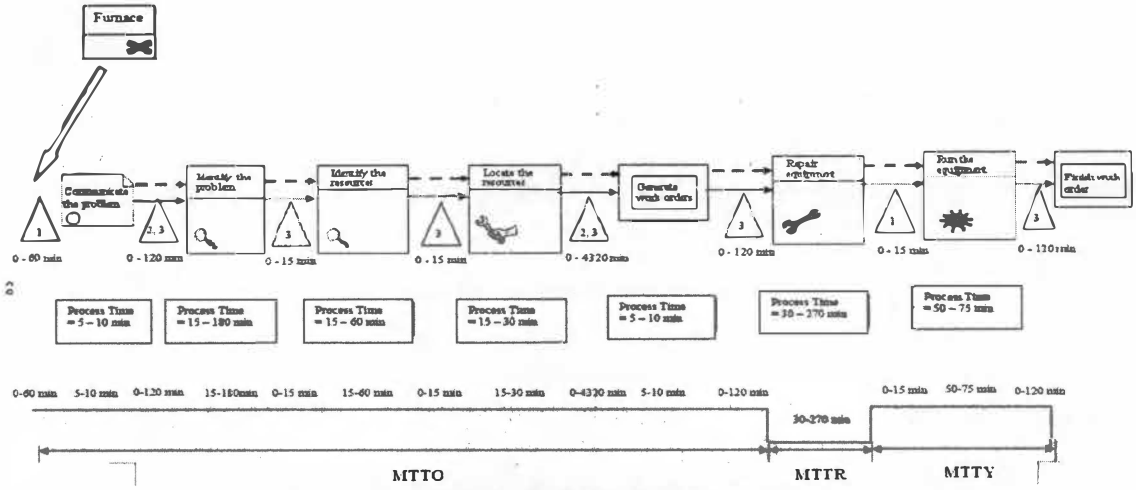


Figure 4.8: Step 7 of MVSM (Case Study)

4.4 Simulation of MVSM

The simulation model proposed in chapter 3 was used to evaluate the maintenance function used in this case study. Based on a four year data, the number of work orders per year for this case study varied from 36 to 83 and the time between each order varied from 1 to 36 days. Since the data for the MVSM parameters include a minimum and a maximum value, uniform distribution was used to simulate all the input values. A snap shot of the simulation input screen is shown in Figure 4.9.

4.5 Results

After getting all the inputs, simulation model was used to automatically calculate MTTO, MTTR, MTTY, MMLT, Non-value added time, Value added time and Maintenance Efficiency. The results obtained from the simulation are shown in Figure 4.10.

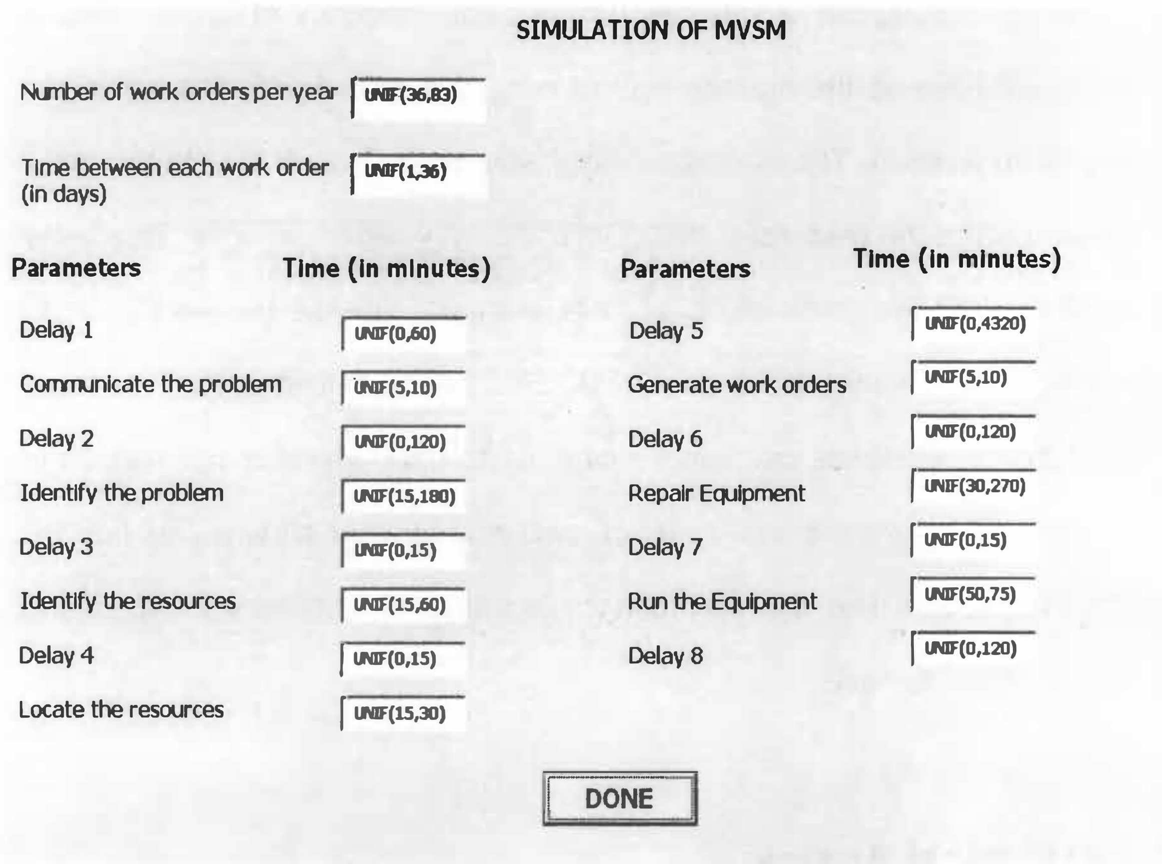


Figure 4.9: Simulation input

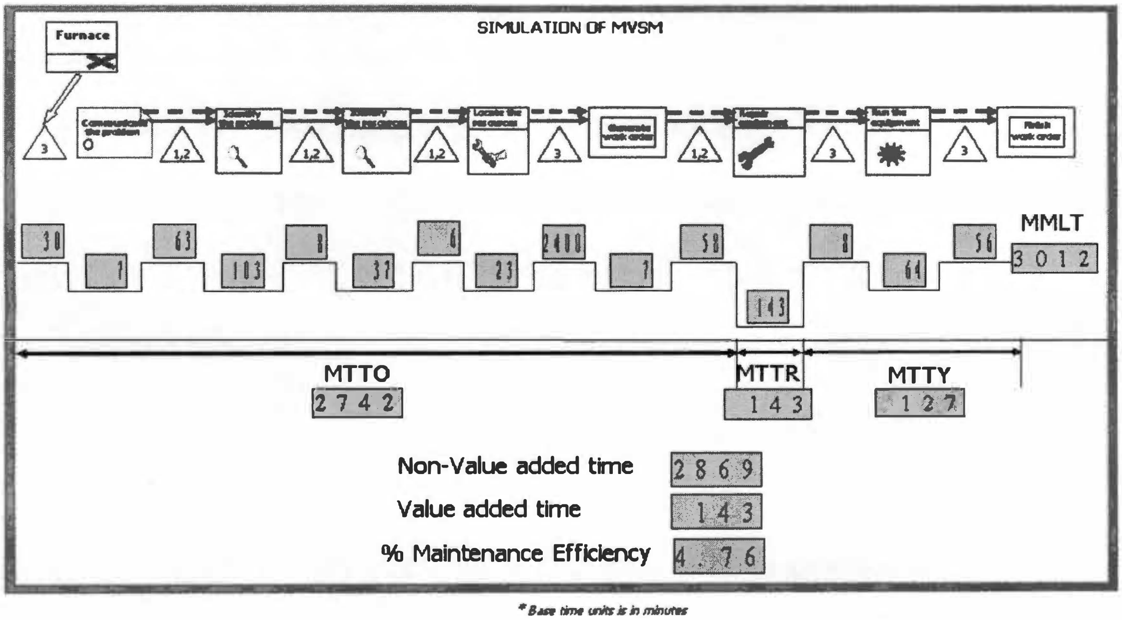


Figure 4.10: Simulation Results

The result suggests a very low maintenance efficiency of 4.76%. This is predominantly due to the high amount of non-value added activities within the maintenance function. The majority of non-value added time is due to the delay between “Locate the resources” and “Generate work order” process. This delay is caused due to the unavailability of tools and parts to issue the work order to perform the necessary maintenance task. This clearly indicates that the focus point of the maintenance personnel should be to have a proper mechanism in place that will ensure the availability of parts and tools at all times as this will significantly stream line the maintenance activities and thereby enhance the availability of the furnace.

4.6 Statistical Analysis

A design of experiment analysis was performed to analyze the impact of MTTO, MTTR, MTTY and their interactions on the response variable i.e. MMLT. Based on 0%, 50% and 100% variation of the case study data, the 3-levels for MTTO was found to be 2742, 4103 and 5389 minutes, for MTTR, the 3-levels were 143, 213 and 279 minutes, and for MTTY, the 3-levels were 127, 183 and 235 minutes. A 3-factor, 3-level full factorial completely randomized design is shown in Table 4.1. A total of 27 simulation runs were made and for each run the MMLT was recorded.

JMP software was used to analyze the data and the result obtained based on the analysis is shown in Figure 4.11

Table 4.1: Full Factorial Design

Pattern	MTTO	MTTR	MTTY	MMLT
123	2742	213	235	3180
332	5389	279	183	5851
222	4103	213	183	4516
311	5389	143	127	5666
321	5389	213	127	5732
111	2742	143	127	3012
132	2742	279	183	3192
223	4103	213	235	4569
232	4103	279	183	4632
122	2742	213	183	3129
212	4103	143	183	4429
133	2742	279	235	3244
221	4103	213	127	4437
121	2742	213	127	3076
231	4103	279	127	4578
322	5389	213	183	5785
331	5389	279	127	5798
323	5389	213	235	5838
213	4103	143	235	4506
233	4103	279	235	4684
211	4103	143	127	4373
333	5389	279	235	5903
313	5389	143	235	5772
112	2742	143	183	3065
312	5389	143	183	5719
113	2742	143	235	3117
131	2742	279	127	3140

Response MMLT
Summary of Fit

RSquare	0.999614
RSquare Adj	0.999472
Root Mean Square Error	25.46417
Mean of Response	4479.37
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	31938828	4562690	7036.585
Error	19	12320	648	Prob > F
C. Total	26	31951148		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-36.63908	33.50208	-1.09	0.2878
MTTO	1.0038286	0.004534	221.39	<.0001
MTTR	1.1119839	0.088251	12.60	<.0001
MTTY	1.0295044	0.111122	9.26	<.0001
(MTTO-4078)*(MTTR-211.667)	1.5465e-5	8.166e-5	0.19	0.8518
(MTTO-4078)*(MTTY-181.667)	5.8657e-6	0.000103	0.06	0.9551
(MTTR-211.667)*(MTTY-181.667)	-0.000645	0.002001	-0.32	0.7506
(MTTO-4078)*(MTTR-211.667)*(MTTY-181.667)	-1.123e-8	1.852e-6	-0.01	0.9952

Prediction Profiler

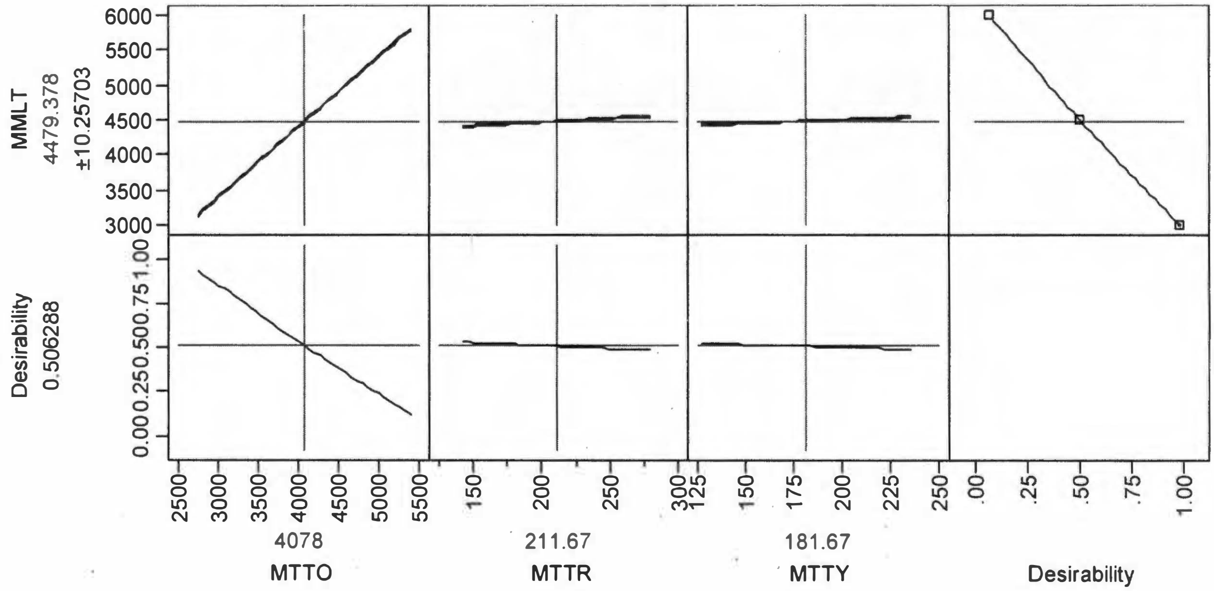


Figure 4.11: JMP Results

The results suggest that the interaction terms are statistically insignificant and only the main terms such as MTTO, MTTR and MTTY are significant. This shows that the interaction terms do not add much to the model in predicting MMLT once MTTO, MTTR and MTTY are calculated. Further the prediction profiler indicates that MTTO is the better predictor of the response MMLT when compared to MTTR and MTTY.

4.7 Conclusion

The MVSM approach was successfully applied to the case study and the simulation model was able to effectively evaluate the maintenance function and display the results. The MVSM approach was also able to indicate the critical areas of non-value added activities, which the maintenance personnel should focus on, in order to significantly reduce MMLT.

Chapter 5

Conclusion

5.1 Introduction

Chapter 5 throws some light on the landmarks achieved by the research work carried out in this thesis, by summarizing all the major conclusions that can be drawn out of it. It also identifies avenues for further research work in this area.

5.2 Summary of Research

There are several conclusions that can be drawn out of the research work performed in this thesis. Firstly, the framework established in chapter 3 provides a list of some of the newly developed MVSM symbols, which can be universally employed by all practioners involved in mapping out the maintenance function. These symbols will also provide the maintenance community with a common language of addressing their maintenance activities.

The step by step standard mapping process developed in this thesis will enable the maintenance practioners to successfully baseline their maintenance activities in terms of the components of MMLT, namely, MTTO, MTTR, and MTTY

The simulation model of MVSM established in this research will reduce the tedious efforts involved in the calculation of MVSM metrics and will also enable the practioners to perform a dynamic evaluation by incorporating variation into any of the MVSM parameters. This model also has the ability to indicate the critical areas of non-value added activities, which will enable the maintenance personnel to focus their attention on those areas, so as to significantly reduce the MMLT.

Overall, the maintenance community now has a tool by which they can effectively evaluate the maintenance function. This in essence will provide scope for reducing the areas of non-value added activities within maintenance and thereby enhancing the availability of the equipment and the capacity of the manufacturing facility.

5.3 Future Work

The MVSM presented in this thesis represent only the current state of the maintenance function. This research work can be further enhanced by developing a structured approach that will transform the current state into a desired future state of the MVSM. The future state will provide a vision for the ideal activities to be performed within maintenance.

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